PUBLICATION 65

ENERGY

CONSERVATION IN ONTARIO GREENHOUSES

Ministry of Agriculture and Food

Ontario

Dennis Timbrell
Minister

Prepared by

T. Blom, Research Scientist, Horticultural Research Institute of Ontario, Vineland Station, Ontario L0R 2E0

F. Ingratta, Research Scientist, Horticultural Research Institute of Ontario, Vineland Station, Ontario L0R 2E0

J. Hughes, Extension Horticulturalist, Ontario Ministry of Agriculture and Food, Brampton, Ontario L6Y 1P7

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INTRODUCTION

The greenhouse industry in Canada is an important component of the horticultural production system. Farm gate value in excess of $225 million, of which 60% was accounted for by Ontario growers, was recorded for 1981. The purpose of a greenhouse structure is to allow for economic cropping under controlled environmental conditions during seasons which do not allow outdoor production. To achieve this objective, the basic greenhouse is constructed to optimize light transmission and maintain uniform temperatures. This results in a poorly insulated building which has high demands for heating and cooling. The high fuel requirements have resulted in significant increases in the cost of greenhouse operation and energy conservation has become a necessity in order to achieve a profitable position. Unfortunately alterations to the design which may be energy conserving but reduce productivity or alter crop scheduling may not prove to be cost effective. The goal then becomes to conserve energy where possible but maintain desirable conditions for plant growth.

In this publication some of the basic principles governing greenhouse heating and various techniques for reduced energy consumption are outlined. Average fuel consumption for year-round crop production in Ontario is approximately 75 litres (L) of No. 2 oil or its equivalent per square metre (m^2) of greenhouse area when a minimum night temperature of 17°C is maintained in a glasshouse. In general, energy represents between 15 and 45% of the annual greenhouse operating costs. This percentage will likely increase as fuel costs continue to rise as projected in Figure 1. By judicious implementation of energy conservation techniques, these values may be reduced by as much as 50% with negligible effects on crop production. Technological developments in the area of renewable energy sources may permit even greater reductions in the consumption of fossil fuels. Energy conservation will allow the greenhouse growers to maintain a viable, essential and productive industry.

An attempt has been made to combine information from sources in North America and Europe to provide an up-to-date summary of energy conservation technology.

The authors wish to acknowledge the help of other research and extension personnel whose comments improved the content of this publication. Moreover our thanks is extended to some greenhouse manufacturers for their schematic drawings.

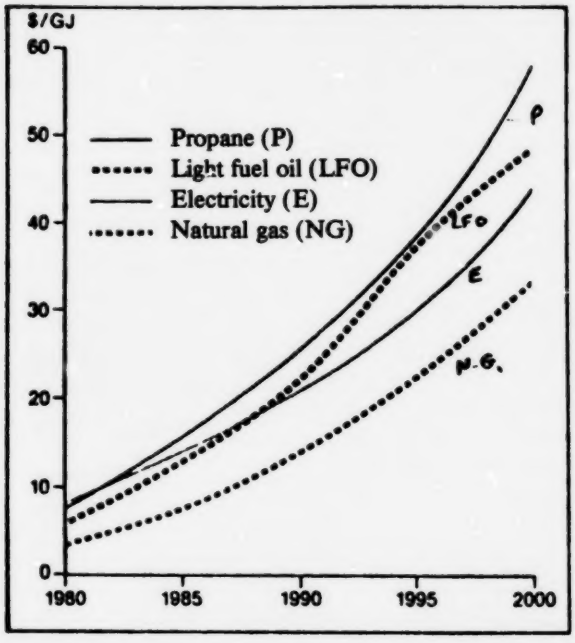


Figure 1. Energy price forecast for heating fuels in agriculture

Note The conversion efficiency (CE) of electricity is assumed to be 100% ; CE of the other three fuels is assumed to be 75%, though in practice it will vary with the furnace. 1 GIGAJOULE (GJ) = 948,000 BTU = energy in one-sixth barrel of oil.

Source Ontario Ministry of Energy, April 1981

PRINCIPLES OF HEAT LOSS FROM GREENHOUSES

The principles of how heat losses from a greenhouse occur, must first be well understood before any attempt is made to devise methods to reduce fuel consumption. The three basic mechanisms for heat transfer are as follows:

1. conduction
2. convection
3. radiation

1. Conduction

Conduction is the heat flow by molecular action within a material, or from one material to another. The composition and the density of a compound determines the heat conductivity. In general, materials with a high density are good conductors. Steel or aluminum are better conductors than wood and this means that wooden rafters allow less heat to pass through then aluminum rafters. Also the conductive heat transfer through air-inflated double plastic is considerably less than through glass.

2. Convection

Convection is the transfer of heat by fluid movement (eg. air). There are two types of convection which play a role in the environment of a greenhouse:

(a) *Forced Convection* is the transfer of heat through a surface exposed to an airstream, proceeding at a rate which depends on the velocity of the flow; and

(b) *Free Convection* depends on the rise of warm air above heated surfaces or the drop of cold air beneath cooled surfaces. Both types of convection are important heat transfer mechanisms within a greenhouse.

Further differentiation of convection can be made when we look at convective heat losses through the surface of a greenhouse. The following two types of convective heat losses can be distinguished:

(1) *Infiltration* Heat is lost by air infiltration through glass laps, holes and cracks. The amount of air infiltration depends on the tightness of the construction, the type of cover used as well as the wind velocity. For a glasshouse it is generally considered that one to four (1 to 4) air changes per hour occur while there is only two-tenths to one (0.2 to 1.0) air exchange per hour for an air-inflated plastic house.

(2) *Ventilation* It is often necessary to reduce the air temperature in the greenhouse by bringing in cool air. However, improperly set or malfunctioning thermostats can cause the greenhouse to be cooled below the desired temperature. Excessive ventilation causes heaters to run longer in order to warm the incoming air. Aspirated thermostats as well as proper maintenance will reduce the temperature fluctuation in a greenhouse.

The heat losses from water condensing on glazing materials is often neglected but can in some cases be substantial. Transpiration of plants requires energy to convert water from a liquid to a vapor state. This energy is obtained from the plant and surroundings. When the moist air condenses on a cold surface (eg. greenhouse glazing) this energy is released and partially lost to the outside of the greenhouse.

3. Radiation

Radiation is a form of energy which is transmitted through space from a substance with a higher temperature to a substance with a lower temperature. Any solid, liquid or gas has the ability to emit and absorb radiation, and this is a continuous process in nature. The spectrum of radiation depends greatly on the surface temperature of the material. For instance the sun (6,000°C) provides radiant energy which has about 50% spectral distribution in the visible light range (wavelengths between 0.4 to 0.8 micron). Only part of the solar radiation arrives at the earth surface since some radiation is absorbed or reflected due to masses of particles and gases in the atmosphere, such as clouds, etc. The remainder of the solar radiation warms up our earth surface. The transmission of solar radiation into a greenhouse depends to a large extent on its covering material (Table 1). The transmittance is defined as the ratio of light passing through a material to the light beaming upon it in a rectangular fashion.

The total amount of radiation received in a greenhouse is also dependent on the area of structural obstacles, the angle of the incident radiation and the cleanliness of the covering material. The total amount of solar radiation received in the greenhouse at plant level is usually between 50 and 70% of exterior levels.

Radiation is also emitted from the soil surface, crop and structural members. The spectral distribution of this radiation is different from that of solar radiation as it occurs primarily in the infrared part of the spectrum (.8 to 18 microns). This is usually described as **Infrared Radiation** or **Thermal Radiation.** Greenhouse covering materials differ greatly with respect to their transmission of infrared radiation (Table 1). Glass and fibreglass have a low transmission factor (less than 10%) and a high reflection factor for infrared radiation. Plastic, on the other hand, acts almost as a sieve since it has a high transmission factor (about 70 to 80%) for infrared. This is the main reason that a plastic greenhouse cools off faster during nights with a clear sky and no wind.

Moisture which often condenses on the inside of a covering material will help to reduce the radiative heat loss from a greenhouse, as water has a high absorption ratio for infrared radiation. Similarly, during the daytime, moisture will also prevent visible radiation from entering the greenhouse.

Table 1. Transmission of shortwave (0.4 to 0.8 micron) and longwave radiation (.8 to 18 microns) of several glazing materials

	Transmission (%)	
	Shortwave Radiation (direct sunlight)	Longwave Radiation
Glass, single	88	4
Polyethylene, single	89	71
Double Acrylic (SDP)	85	0
Double Polycarbonate (SDP)	78	3
Polyester	90	16
PVC-Film	91	12
Double Glass	75	2
Fiberglass	78	1

The leaf temperatures of a greenhouse crop are often lower than air temperature during the night. This is especially true on cold nights and clear skies. If the infrared radiation can be reflected back by a reflective surface, such as a thermal screen, the temperature of leaves will be close to that of air.

The relative amounts of total heat loss from a greenhouse due to either conduction, convection or radiation are very difficult to estimate. The type of structure, covering material, wind velocity, cloudiness, inside as well as outside temperature and other variables are all important factors.

In general, one may say that radiation losses from glasshouses are considerably less than from air-inflated plastic houses. However, convective and conductive heat losses from glasshouses are significantly higher than from plastic houses.

HEAT LOSS CALCULATIONS

To illustrate the principles of heat loss in a mathematical manner, we distinguish heat loss by conduction (Q_C) and heat loss through natural air exchange (Q_A) with:

$$Q_C = U \cdot A \cdot \Delta T \quad [W]$$

where Q_C = heat transfer through a material, Watt [=W]

U = overall heat transfer coefficient, $W/(m^2 \cdot °C)$

A = exposed surface area, m^2

ΔT = temperature differential between inside and outside, °C.

The infiltration heat transfer equation, Q_A, is

$$Q_A = 0.373 \times \Delta T \times GV \times NAE \quad [W]$$

where 0.373 = constant representing the heat content of air

GV = greenhouse volume, m^3

NAE = number of natural air exchanges per hour

Radiative heat losses are very difficult to quantify because they depend greatly on the presence of radiating surfaces within the greenhouse as well as outside weather conditions and are for all practical purposes included in the conductive heat loss, Q_C.

The total heat loss (Q_T) for a greenhouse can then be given as

$$Q_T = Q_C + Q_A \quad [W]$$

If we look at the conductive heat transfer (Q_C) we may observe that there are different ways to reduce the heat loss from a greenhouse. Decreasing the exposed surface area of the greenhouse, lowering the inside air temperature and/or decreasing the U-value will help to decrease the heat loss.

Air infiltration rates that can be expected in various types of greenhouses are listed in Table 2, while heat transfer coefficients (U-values) for typical greenhouse coverings (A), construction materials (B) and thermal curtains (C) are presented in Table 3. The lower the U-value the smaller the expected heat loss.

Table 2. Air exchanges for greenhouses

Construction system	Air exchanges per hour*
1. New construction, glass or fibreglass	0.75 to 1.5
2. New construction, double layer polyethylene	0.2 to 1.0
3. Old construction, glass, good maintenance	1 to 2
4. Old construction, glass, poor condition	2 to 4

**Low wind or protection from wind reduces the air exchange rate.*

Table 3. Heat transfer coefficients for several greenhouse materials

Materials	U-value [W/(m²°C)]
A. Glazing materials	
Glass, single layer, 3 mm thick	6.45
Glass, double layer, 6 mm air space	3.70
Glass, triple layer, 6 mm air spaces	2.66
Polyethylene film, single layer	6.53
Polyethylene film, double layer, separated by air	5.0 (est.)
Fiberglass, flat (for corrugated, 15% more)	5.68
Double acrylic (SDP-16 mm)	3.12
Coroplast (4 mm thick polypropylene)	4.65
Glass and bubble film (12 mm thick)	3.3
B. Construction materials	
Concrete block, 20 cm, 2 core	2.90
Concrete block, 20 cm + 2.5 cm foamed urethane	0.74
Concrete block, 20 cm + 2.5 cm foamed polystyrene	1.02
Concrete, poured, 15 cm	4.27
Cement asbestos board, 0.6 cm	6.24
Cement asbestos board, 0.6 cm, plus 2.5 cm foamed urethane	0.79
Cement asbestos board, 0.6 cm, plus 2.5 cm foamed polystyrene	1.19
Polystyrene (styrofoam), extruded expanded, 1.25 cm thick, Type 4	2.17
Polystyrene (styrofoam), extruded expanded, 2.50 cm thick, Type 4	1.14
Polystyrene (beadboard), expanded, 2.50 cm thick, Type 2	1.42
Polyurethane, cutboard, 2.50 cm thick	0.97
Aluminized urethane board, 1.90 cm thick	1.15
Polyurethane foam (applied at site), 2.5 cm thick	0.96
Softwood board, 2.5 cm nominal	3.17
Perimeter – uninsulated (per metre length, W/(m.°C))	2.77
Perimeter – insulated (per metre length, W/(m.°C))	1.39
Vermiculite, expanded, 65-95 kg/m³, 2.5 cm thick	2.58
C. Thermal curtains	
AL/Temp, aluminum down	4.0
AL/Temp, aluminum up	4.76
AL/Blac	4.17
Duracote No. 2425 (Foylon)	2.17
Black Sateen	3.70
Black polyethylene, 150 micron	5.56
Clear polyethylene, 50 or 100 micron	6.53
Reemay, spunbonded polyester, 2016	6.67
Vinyl (aluminized polyester laminated vinyl), 115 micron	2.63
Terylene LS 55, white	N/A
Terylene LS 100, black	N/A
Thermoshade 1	N/A
Thermoshade 2	N/A
Fibertex	N/A
Fibertex, Pora 73, black	N/A
Fibertex. 75 Aluminized black	N/A

Note re A. The heat transfer coefficients for glazing materials are based on the assumption of a wind velocity of 25 km/h on the outside and no wind on the inside.

re C. The heat transfer coefficients are approximate values because moisture content of material and air movement on both sides of the material are important.

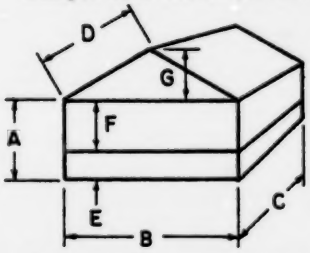
The following worksheets can be used to make heat loss calculations for a single gable roof, single curved roof, and gable or curved roof ridge and furrow greenhouse under a specific set of conditions. No contribution from solar radiation is incorporated in these calculations.

A. Worksheet for single gable roof

The six steps of the calculation procedure are:

1. List dimensions
2. Calculate surface areas
3. List construction materials of outer surfaces and their U-value
4. Calculate conductive heat loss, Q_C
5. Calculate air infiltration heat loss, Q_A
6. Add to get total heat loss, Q_T

Sample heat loss calculation procedure



Minimum desired inside temperature, 16°C (T_{inside})

Minimum expected outside design temperature, –18°C ($T_{outside}$)

Calculate the expected heat loss from a single house covered by a single layer of glass. The house is old construction, but the glass fits fairly tight. The sidewall has 60 cm of cement asbestos board and 1.80 m of glass. The foundation is not insulated. The minimum expected outside design temperature, i.e. –18°C, is the Toronto design temperature for January.

Step 1. List greenhouse dimensions in metres

Wall height, A	= 2.4 m
House width, B	= 12.0 m
House length, C	= 30.0 m
Rafter length, D	= 6.7 m
Lower wall height, E	= 0.6 m
Upper wall height, F	= 1.8 m
Gable height, G	= 3.0 m

Step 2. Calculate surface areas and perimeter for single gable house

1. Lower wall area = E x 2B +E x 2C	= 50.4 m²
2. Upper wall area = F x 2B + F x 2C	= 151.2 m²
3. Gable end area = 2 (B x G/2)	= 36.0 m²
4. Roof area = 2(D x C)	= 402.0 m²
5. Perimeter = 2B + 2C	= 84.0 m

Step 3. List materials of construction for each surface and U-values from **Table 3.**

Location	Materials of construction	U-value
1. Lower wall area	cement-asbestos board 0.6 cm	$U_1 = 6.25$
2. Upper wall area	glass, single	$U_2 = 6.45$
3. Gable end area	glass, single	$U_3 = 6.45$
4. Gable roof area	glass, single	$U_4 = 6.45$
5. Perimeter	insulated	$U_5 = 1.39$

Step 4. Calculate conduction loss, Q_C. Round number to the nearest 100 W.

$Q_C = U \cdot A \cdot \Delta T$ where $\Delta T = T_{inside} - T_{outside}$

1. Lower wall area x ΔT x U_1	= 10,700 W
2. Upper wall area x ΔT x U_2	= 33,200 W
3. Gable end area x ΔT x U_3	= 7,900 W
4. Roof area x ΔT x U_4	= 88,200 W
5. Perimeter x ΔT x U_5	= 4,000 W
Q_C	= 144,000 W

Step 5. Calculate air infiltration heat loss, Q_A. Between 1 and 2 air changes per hour can be expected for an old glass covered house in good repair (Table 2). Assume a rate of 1.5 air changes per hour.

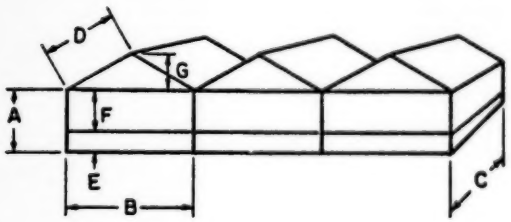
Volume of gable house = (A x B x C) + 1/2 (B x G x C)
= 1,404 m^3

Q_A = 0.373 x ΔT x GV x NAE
= 0.373 x 34 x 1,404 x 1.5 = 26,700 W

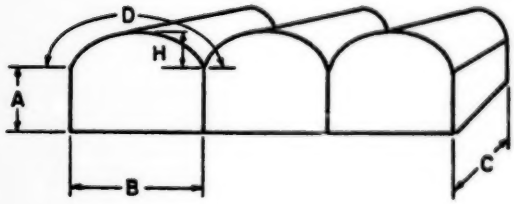
Step 6. Total greenhouse heat loss, Q_T

$Q_T = Q_C + Q_A$ = 144,000 + 26,700 = 170,700 W
for a 360 m^2 glass greenhouse or 474 W/m^2

B. Worksheet for gutter connected greenhouses



Ridge and furrow gable house



Ridge and furrow curved roof house

Note: Use appropriate equations for your greenhouse.

Step 1. List greenhouse dimensions in metres

Wall height, A	=	m
House width, B	=	m
House length, C	=	m
Rafter length, D	=	m
Lower wall height, E	=	m
Upper wall height, F	=	m
Gable height, G	=	m
Roff rise, H	=	m
Number of houses, N	=	

Step 2. Calculate surface areas and perimeter for ridge and furrow gable roof. N is the number of individual house sections forming greenhouse.

1. Lower wall area =2(E x C) + 2N(B x E)	=	m^2
2. Upper wall area = 2(F x C) + 2N(B x F)	=	m^2
3. Single material wall area = 2(A x C) +2N (A x B)	=	m^2
4. Gable end area = 2N (B x G/2)	=	m^2
5. Curved end area = $\frac{2NH(2B)}{3}$	=	m^2
6. Gable roof area = 2N(D x C)	=	m^2
7. Curved roof area = N(D x C)	=	m^2
8. Perimeter length = 2(C + NB)	=	m

Step 3. List of materials of construction for each surface and U-values from Table 3.

Location	Materials of Construction	U-values
1. Lower wall area		U_1 =
2. Upper wall area		U_2 =
3. Single material wall		U_3 =
4. Gable end area		U_4 =
5. Curved end area		U_5 =
6. Gable roof area		U_6 =
7. Curved roof area		U_7 =
8. Perimeter length		U_8 =

Step 4. Calculate conductive heat loss, Q_C.

$Q_C = U \cdot A \cdot \Delta T$ where $\Delta T = T_{inside} - T_{outside}$

1. Lower wall area x ΔT x U_1	=	W
2. Upper wall area x ΔT x U_2	=	W
3. Single material wall area x ΔT x U_3	=	W
4. Gable end area x ΔT x U_4	=	W
5. Curved end area x ΔT x U_5	=	W
6. Gable roof area x ΔT x U_6	=	W
7. Curved roof area x ΔT x U_7	=	W
8. Perimeter length x ΔT x U_8	=	W
Q_C	=	W

Step 5. Calculate air infiltration heat losses, Q_A

Volume of gable house = N (A x B x C) + 0.5 N (B x G x C)

or Volume or curved house = N (A x B x C) + 0.67 N (H x B x C)

Q_A = 0.373 x ΔT x GV x NAE

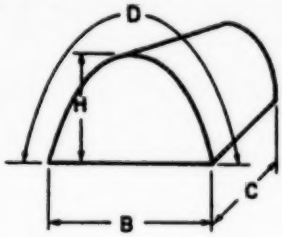
Step 6. Total greenhouse heat loss, Q_T

$Q_T = Q_C + Q_A =$ W

C. Worksheet for quonset type greenhouse

Step 1. List greenhouse dimensions in m.

House width, B =
House length, C =
Rafter length, D =
Roof rise, H =



Single curved roof house

Step 2. Calculate surface areas and perimeter.

Curved roof area = D x C	=	m^2
Curved end walls area = 1.33 x H x B	=	m^2
Perimeter = (2B + 2C)	=	m

Step 3. List materials of construction and U-values from Table 3.

Location	Materials of construction	U-values
Curved roof		U_1 =
Curved endwall		U_1 =

Step 4. Calculate conduction heat, Q_C

$Q_C = U \cdot A \cdot \Delta T$ where $\Delta T = T_{inside} - T_{outside}$

Curved roof area x $\Delta T/U_1$ = W

Curved endwall area x $\Delta T/U_2$ = W

Q_C = W

Step 5. Calculate air infiltration heat losses, Q_A

Volume of curved roof house + 0.67 x H x B x C = m^3

$Q_A = 0.373 \times \Delta T \times GV \times NAE$

Step 6. Total greenhouse heat loss, Q_T

$Q_T = Q_C + Q_A =$ W

Comparative heat loss calculations for three different types of greenhouses

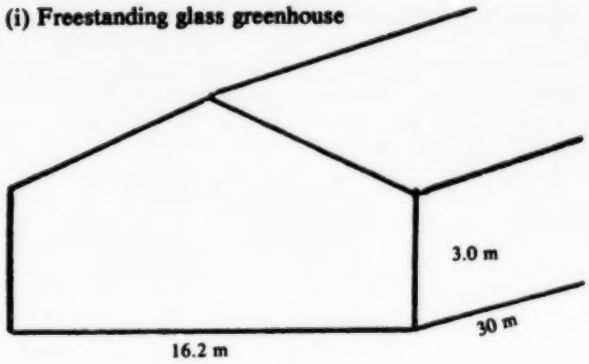
For these calculations, some of the most commonly used greenhouse types in Ontario have been chosen, namely (i) freestanding glass greenhouse, (ii) gutter connected glass greenhouse and (iii) gutter connected air-inflated plastic house.

The calculations are based on the formulas presented in the previous sections. Some of the additional assumptions are:

(a) the greenhouse(s) cover(s) a surface area of 486 m^2; gutter height is 3.0 m;
(b) the temperature differential, ΔT, is 34°C;
(c) for the glass greenhouses the bottom .60 m of the sidewall is made of cement asbestos. The double plastic greenhouse has corrugated fiberglass as sidewall;
(d) air changes per hour are one in the glasshouses and one-half in the double poly house.

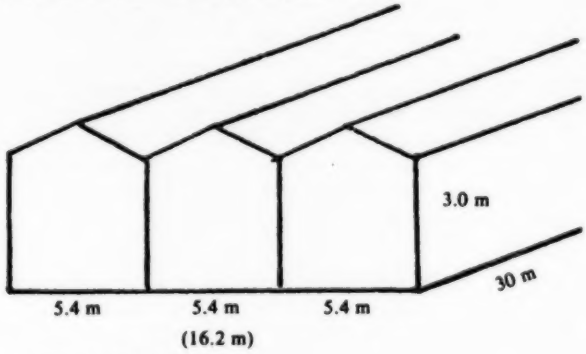
The calculated heat losses for the different structures are:

(i) Freestanding glass greenhouse



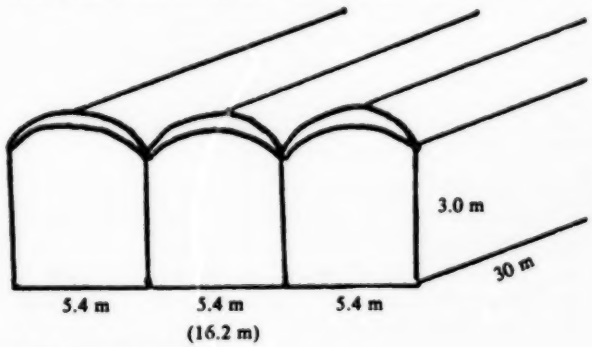
Q_C = 209,500 W
Q_A = 30,800 W
Q_T = 240,300 W

(ii) Gutter connected glass greenhouse



Q_C = 188,000 W
Q_A = 22,700 W
Q_T = 210,700 W

(iii) Gutter connected air-inflated plastic greenhouse



Q_C = 153,300 W
Q_A = 12,300 W
Q_T = 165,600 W

The following observations can be made from the calculations:

– The gutter connected greenhouse has a lower heat loss (about 12% less) than the freestanding glass house;

– The air inflated plastic house shows a 21% smaller heat loss than a similar glass house;

– Heat losses through natural air exchange accounts for about 10% of total heat loss (assuming no strong winds!) in a glasshouse.

Heat losses through the roof represent about 65% of the total heat loss while the sidewalls and perimeter account for the remainder, if we assume that the heat loss characteristics for the roof are similar to that of the sidewall. It should be remembered that differences in radiative heat losses have not been considered in these calculations because the heating system, type of glazing material and outside weather conditions have to be known. Also, no adjustments have been made for the type of rafters (wood or aluminum), the spacing of the rafters or the number of gutters.

Seasonal heat demand

The previous heat loss calculations are given for an extreme situation, since it is used to calculate the design requirements of a heating system. Calculations can also be made for ambient conditions and incorporating the effects of solar radiation. Such an exercise will provide a heat demand on an annual basis. The results are presented in Table 4. The average amounts of heat required during the night and daytime respectively, based on temperatures in and outside the greenhouse are listed in columns (1) and (2). The "Effective Radiation" (column 3) is the amount of solar radiation received in a greenhouse. This is estimated to be about 60% of the total radiation received at a horizontal surface.

Table 4. Monthly heat balance for a 4080 m^2 glass greenhouse maintaining a night temperature of 17°C and a day temperature of 20°C for southern Ontario (x 10^6 kJ/month)

	Night* (1)	Day** (2)	Effective Radiation (3)	Net Day (4)	Night + Net Day (5)	Monthly Demand(%) (6)	Fuel Requirements (L/m^2) (7)
Jan.	1880	1040	- 324	716	2600	23.3	21.8
Feb	1470	958	- 549	409	1880	16.9	15.7
Mar	1110	808	- 970	-	1110	10.0	9.3
Apr	708	552	-1210	-	708	6.4	5.9
May	428	181	-1580	-	428	3.8	3.6
June	150	-	-1650	-	148	1.3	1.2
July	25	-	-1620	-	25	0.2	0.2
Aug	66	-	-1380	-	66	0.6	0.5
Sept	241	-	-1010	-	241	2.2	2.0
Oct	673	355	-650	-	673	6.0	5.6
Nov	1040	530	-365	165	1200	10.8	10.0
Dec	1580	768	-305	463	2040	18.4	17.1
Yearly Total	9,370	5,190	-11,600	1,750	11,100	100.0%	93 L/m^2

Note **The requirements during the night are based on the average minimum temperature during the month (weather data, Vineland Station).*

***The day requirements are based on the average maximum temperature during the month (weather data, Vineland Station).*

The "Net Day" (column 4) gives the overall heat requirement during the daytime as summations of columns (2) and (3). The heat requirements on a monthly basis is given in column (5) for this particular type of greenhouse. It is interesting to note that the annual "Effective Radiation" (column 3) is about one-half of the total annual heat requirement (column 5). The monthly heat demand is given as a percentage in column 6 or a year-round operation. The months December, January and February account for about 58% of the annual demand. An equivalent monthly fuel consumption is given in column (7) when using No. 2 fuel oil with an overall efficiency of 75%. Due to the assumptions made, the heat requirements are about 15% higher than empirical figures. Although this table does not incorporate additional heat for soil pasteurization or to control excess relative humidity it should assist the grower in deciding whether or not to close down during the winter months.

FUEL COST COMPARISONS

In order to compare costs of different fuels, the heat content per unit of fuel (Table 5) should be known. In this table a 100% combustion efficiency is assumed. Actual burner efficiency will range from 60 to 90% depending on fuel source and burner type. To compare the actual costs of various fuels, Table 6 has been generated. It will help to compare the price of one fuel with another. For example if you presently pay 20¢/L for No. 2 fuel oil, you can pay for an equivalent amount of heat:

- 22.0 ¢/L for No. 6 bunker oil
- 13.1 ¢/L for liquid propane
- 19.3 ¢/m^3 for natural gas
- $151./tonne for coal
- 1.8 ¢/kWh for electricity

When comparing fuel types, factors other than the equivalent fuel costs to consider are:

(a) overall conversion efficiency;
(b) annual fuel consumption (Table 7);
(c) cost of conversion of burner to new fuel;
(d) relative maintenance (burner) costs;
(e) future availability of fuel source;
(f) price of fuel in future (Figure 1); and
(g) relative ease of storage and/or delivery.

Table 5. Equivalent heat values of common fuels

Type of fuel 1/	Heat content 2/
No. 2 Fuel oil	39 MJ/L
No. 6 Bunker oil	42.8 MJ/L
Liquid propane	25.6 MJ/L
Natural gas	37.6 MJ/m^3
Coal (hard)	29,500 MJ/tonne
Electricity	3.6 MJ/kWh
Straw	14,000 MJ/tonne
Wood (dry)	20,000 MJ/tonne

1/ 1L No. 2 oil = 0.91 L No. 6 oil = 1.52 L of propane = 1.04 m^3 of natural gas = 1.32 kg of coal = 10.8 kWh of electricity (=39 MJ)

2/ Megajoule is equivalent to 948 BTU, also see conversion table in back.

Table 6. Comparative fuel costs for an equivalent amount of heat

Fuel Oil No. 2 (¢/L)	Bunker Oil No. 6 (¢/L)	Liquid Propane (¢/L)	Natural Gas (¢/m^3)	Coal ($/tonne)	Electricity (¢/kWh)	MJ of heat produced by 1¢ of fuel
12	13.2	7.9	11.6	91	1.1	3.3
13	14.3	8.5	12.5	98	1.2	3.0
14	15.4	9.2	13.5	106	1.3	2.8
15	16.5	9.9	14.5	113	1.4	2.6
16	17.6	10.5	15.4	121	1.5	2.4
17	18.7	11.2	16.4	128	1.6	2.3
18	19.8	11.8	17.4	136	1.7	2.2
19	20.9	12.5	18.3	144	1.8	2.1
20	22.0	13.1	19.3	151	1.8	2.0
21	23.1	13.8	20.2	159	1.9	1.9
22	24.2	14.5	21.2	166	2.0	1.8
23	25.3	15.1	22.2	174	2.1	1.7
24	26.4	15.8	23.1	181	2.2	1.6
25	27.5	16.4	24.1	189	2.3	1.6
26	28.6	17.1	25.1	197	2.4	1.5
27	29.7	17.7	26.0	204	2.5	1.4
28	30.8	18.4	27.0	212	2.6	1.4
29	31.9	19.1	28.0	219	2.7	1.3
30	33.0	19.7	28.9	227	2.8	1.3
31	34.1	20.4	29.9	234	2.9	1.3
32	35.2	21.0	30.9	242	3.0	1.2
33	36.3	21.7	31.8	250	3.1	1.2
34	37.4	22.3	32.8	257	3.2	1.2
35	38.5	23.0	33.7	265	3.3	1.1
36	39.6	23.6	34.7	272	3.4	1.1
37	40.7	24.3	35.7	280	3.5	1.1
38	41.8	25.0	36.6	287	3.6	1.0
39	42.9	25.6	37.6	295	3.7	1.0
40	44.0	26.3	38.6	302	3.8	1.0

Table 7. Relative fuel usage for year-round production in Southern Ontario

Night Temperature	Glasshouse		Double Polyethylene House	
	Natural Gas	No. 2 Oil	Natural Gas	No. 2 Oil
14°C	60 m^3/m^2	58 L/m^2	45 m^3/m^2	43 L/m^2
18°C	90 m^3/m^2	87 L/m^2	67 m^3/m^2	65 L/m^2
22°C	120m^3/m^2	116 L/m^2	90 m^3/m^2	87 L/m^2

CONSERVATION TECHNIQUES

There are several energy conservation techniques that can be applied to a greenhouse. They can be grouped into the following categories:

A. Reducing the overall heat transfer coefficient (U)
B. Lowering the temperature differential (ΔT)
C. Optimizing fuel conversion efficiency
D. Reducing energy input per unit product

A. Reducing The Overall Heat Transfer Coefficient (U)

1. Liners

A lining of polyethylene film on the inside of the greenhouse can reduce heat loss substantially. A savings of 25% can be expected with a light loss of approximately 14% with a single layer of polyethylene. The effect of the poly liner is dependent upon the tightness of the house. Infiltration, particularly on windy nights is greatly reduced by the internal layer of plastic.

Internal poly liners are particularly applicable in free-standing houses where the snow load can melt off more readily than on gutter-connected houses. It is also easier to apply on wooden-barred houses. Because of the light reduction factor, it is only recommended on houses with less light sensitive crops such as foliage. The internal liner is one of the most cost effective ways of conserving energy. Consult your insurance agent to be certain your snow load coverage is not void.

2. Fixed horizontal curtains

Fixed horizontal insulating curtains inside the greenhouse are not recommended in Ontario. Horizontal surfaces reflect light back out of the greenhouse during winter months when light is critical. More seriously, if the roof is insulated, the greenhouse may collapse during a heavy snowfall. For this reason a fixed interior horizontal curtain may void any insurance on the building. Non-porous liners such as polyethylene will trap condensation from the roof.

3. Polyethylene over glass

(i) Single layer

A relatively new idea from Cornell University is a single layer of polyethylene cover over glass. There is less material cost, less light loss and only slightly less energy saved compared to the double polyethylene over glass system.

A length of polyethylene (lay-flat) tubing is stretched from one end of the greenhouse to the other, halfway between the eaves and the peak (Figure 2). Tubing with a diameter of about 50 cm works well. One end of the tube is sealed airtight – either mechanically or through heat sealing. Then a single layer of polyethylene (preferably 150 micron thickness) is placed over the roof and the lay-flat tubing. The edges of the poly sheet can be fixed to the edges of the roof with aluminum extrusions, or even with wooden batten strips. For convenience and permanence, aluminum extrusions are recommended. The sealed end of the lay-flat tubing may also be clamped by extrusions.

The free end of the lay-flat tubing is then fastened to a small inflation blower – like that used to inflate double layer plastic greenhouses. Be sure to use outside air for inflation. Warm, humid air from inside the greenhouse will cause condensation within the lay-flat tubing.

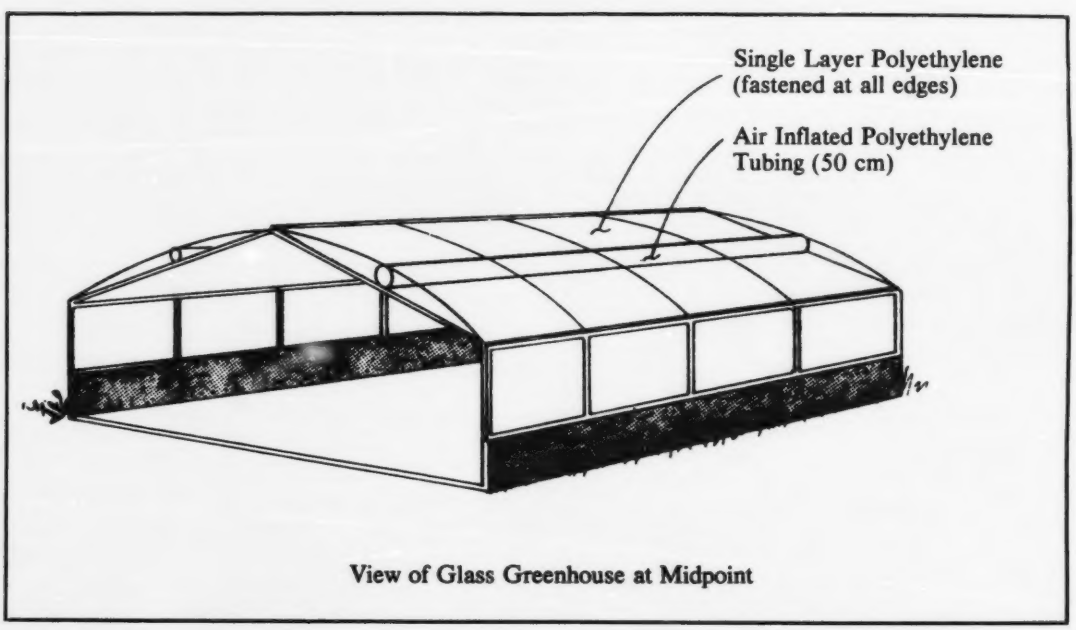


Figure 2. Sketch showing single poly over glass using the inflated-tube method

(ii) Air inflated double polyethylene

The use of double covering, air inflated plastic over glass is becoming widespread. Ohio State has reported energy savings of 57%, and although yields of some crops are less, the net effect is a savings of dollars to the grower. Results recorded at the Vineland Station show a 40% energy reduction but light loss has resulted in significantly lower yields of cucumbers and tomatoes.

Maximum Span

The rafter length should be about 5.5 m because that is the maximum recommended span for an air inflated covering. For greenhouses with longer rafter lengths, the film should be attached to the greenhouse with holddown strips every 5.5 m. If 6.1 m diameter polyethylene tubing is used, the film can be run up and down the rafter and fastened at the 6 m mark or at a main member of the greenhouse framing. A simple manifold of 8 cm PVC pipe can be made to join the side by side sections together.

Maximum recommended inflated liner span.

Light Reduction

One of the disadvantages of double plastic is the result of light reduction. The Ohio study measured a solar radiation reduction of 35% within a conventional glass greenhouse. After the double plastic was installed, an additional 11% light reduction was measured. The plastic cover tended to diffuse the light more uniformly within the greenhouse and structural shading was less apparent. A further reduction of 2% can be expected in the second year.

In the same study, daytime relative humidity during winter months (while vents were closed) measured 12% greater in the plastic covered greenhouse than in the conventional glasshouse.

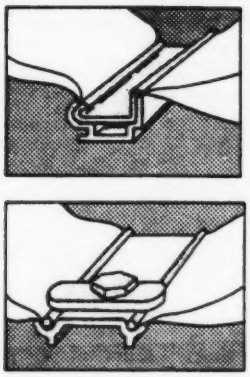
Light sensitive crops such as roses, carnations, cut chrysanthemums and cucumbers may have a significant reduction in quality and production. Some European research indicates that for each percentage of light loss there is a corresponding reduction in crop production during the winter. On east-west oriented glasshouses, applying a double layer of poly on only the northern exposed roof should be considered. This probably would not interfere as much with winter light.

Equipment and Materials Covering

Cover with an ultraviolet light (UV) resistant plastic film manufactured for greenhouse use, which should last two years. Use a 15 micron sheet for both the inner and outer layer.

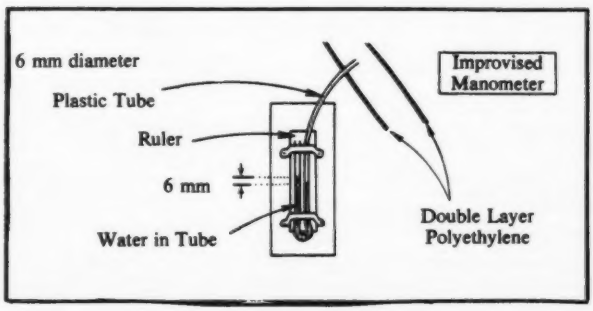
Fasteners

Fastening devices are available from most plastic greenhouse manufacturers. An aluminum or metal rail plus insert is recommended.



Inflation

Inflate with a 50 W centrifugal blower with about a 10 cm diameter x 5 cm wide wheel and a maximum output pressure of 0.145 kPa water column. Install one blower for every 900 m^2 of greenhouse area. Mount the blower before installing the plastic. Place the blower above the snowline so air can be drawn from outside the greenhouse to reduce condensation between the layers.



Build a damper for the blower intake to regulate air pressure. Duct the blower to the plastic film with a 10 cm flexible clothes dryer duct and duct tape. Make a "U" tube manometer as shown to measure pressure between the plastic layers. Maintain about 6 mm of water pressure.

Costs

The material cost for plastic, inflation fans and polylocks is $3 per m^2 of greenhouse. Installation costs vary from $1 to $5 per m^2 depending on the amount of repairs needed, cost of labor, etc.

Installation of Air Inflated Cover for Glass Greenhouses

(a) Remove all sharp protruding objects from the outside surface of the greenhouse to prevent puncturing or tearing of plastic during application.

(b) Obtain plastic securing devices to achieve uniform and secure fastening. It is very important that the securing device be firmly fastened to the greenhouse.

(c) Sash bars must be firmly attached to the gutter plate before securing devices are fastened to them. Repair weak sash bars or attach the plastic securing device to the gutter.

(d) Attach plastic securing devices to the bottom of the sash bars and just below the vents if the vents are used. Bolt through the bars to metal to be secure.

(e) Wash outside glass with glass cleaning compound or water and brush to insure better light transmission through glass. The outside glass should be moist before applying the glass cleaning compound through a sprayer. Let it stand for two or three days then rinse it off with a hose or let the rain wash it off. Suggested compound: 3 kg 98% oxalic acid in 100 L of water.

(f) If top vents are not being used and the total length of the roof from gutter to gutter is less than 12 m, attach securing devices at the gutters and over the entire greenhouse with two single sheets of plastic.

(g) If the greenhouse is longer than available plastic, a transition fastener can be located at one of the sash bars. The same fasteners are often used at the end of the roof.

(h) On a calm day, roll out the plastic over the greenhouse super-structure. A portable scaffold is very helpful for this job.

(i) Fasten the plastic film with the securing devices. Avoid excessive pulling and stretching of the plastic before or during securing since all wrinkles will disappear after inflation. Straps or tiedowns across the top of the plastic sheets are not recommended since they are more likely to tear the plastic than hold it in place.

(j) Once both sheets of plastic are secured, attach the blower duct to the bottom layer of plastic.

(k) Begin inflating. Insert manometer when the plastic is inflated. Regulate the intake damper to maintain a pressure of 6 mm of water.

4. Moveable Interior Blankets

In the section on Heat Loss Calculations it was shown that most of the heat loss from a greenhouse is through the roof (about 65%) and sidewalls (30%). Radiation and conduction are the major contributors to these heat losses with 65 to 80% occurring at night; therefore it seems logical to consider thermal blankets that can be opened or closed when desired. Moveable interior screens or blankets are gaining rapid acceptance due to their cost effectiveness.

An additional feature of an internal blanket system is that some materials (eg. Reemay) can be used to provide partial daytime shading.

(i) Fuel Savings

The heat retention values (U-factors) of some of the available blanket materials are cited in Table 3. The lower the U-value the better the heat retention. It should be noted that the actual savings in any greenhouse depends upon many variables. Tightness of seal around the blanket edges, physical condition of the greenhouse, operating temperatures, ratio of the area of blanket to the greenhouse surface and construction materials for both the greenhouse and blanket are some of these variables. Research has indicated that total fuel savings of 30 to 40% are possible when the curtain is closed or a total annual savings of up to 20-30%.

(ii) Types of Systems

A system can be designed to pull the thermal curtain horizontally from gutter to gutter or from truss to truss (bay to bay). The main difference between these two types is that in the first system the curtain may be stored under the gutter, while in the second case it is stored near a truss. Another important consideration is the length of seal obtained per surface area of greenhouse.

It is also possible to have the thermal curtain follow the contour lines of the greenhouse (gutter-peak-gutter). In this case the material is usually pulled from truss to truss. The shading factor during storage of the curtain must be considered in conjunction with the ease of installation.

There is also a difference in the way the material is supported. Strong materials can be suspended from low-friction pulleys while a weaker material has to be supported and pulled over lines.

The type of crop, orientation and dimensions of the greenhouses are additional factors. In general though, horizontal blankets are considered to be better heat savers (about 10 to 15%) than curtains which follow the contour line.

(iii) Choice of Materials

Material choice is dependent on whether the system is to be used for both energy conservation and black-out or shading. For optimal energy savings the material should have a low emissivity upper surface (eg. aluminum) and a high emissivity lower surface (eg. black). For greenhouse purposes a thermal curtain should be able to permit moisture to pass through. A porous thermal material will reduce the relative humidity buildup under the curtain. It will also allow condensation from the roof to pass through it. The beneficial aspects of a porous thermal curtain should be weighed against its reduced heat retention capabilities.

The material should have sufficient structural strength and maintain its integrity for its expected lifespan. Greenhouse conditions (high relative humidity and ultraviolet radiation) can be harsh on the material and result in ripping and/or algae growth on cloth. The curtain should be flexible and lightweight and fold into a relatively small volume when stored during the daytime; minimum shading by the stored curtain as well as minimum interference with daily activities is desired.

The longevity of the material depends on the type of fabric. Acrylic compounds are the strongest (lifespan 5 to 10 years), while the commonly used polyester materials last about 3 to 5 years. Polyethylene will last 1 to 2 years. Unsuitable materials are polypropylene, polyamid and cellulose. Shrinkage is often overlooked; acrylic has a tendancy to shrink severely; while polyester and polyethylene are more stable.

(iv) Location of Heating System

The primary heat distribution systems must be located within the blanketed area. In case of retrofitting, one could consider the possibility of an extra thermal truss from which the heating pipes can be suspended. Another alternative is placing the heat pipes above the ground, on gutter posts or under benches. Some crops may require additional air circulation within the blanketed area.

(v) Snowload

In Ontario, a system must be provided to prevent structural damage from snow accumulation. A special alarm system costing approximately $400 can be installed to warn of excessive snow accumulation. The monitor-system can activate the mechanism to open the thermal curtain, turn on additional gutter heat lines and/or sound an alarm.

(vi) Insurance

If you install a thermal curtain your greenhouse insurance company should be advised so that any adjustments in premiums and/or coverage can be made.

(vii) Cost

A basic problem with mechanical blanket systems is that individual designs are needed for each greenhouse. Retro-fitting needs customized systems to allow for interior posts, low ceilings, heat distribution systems, handling equipment, etc. Thermal blankets usually come in standard sizes (eg. 2 m) and often have to be extended by sewing, heat sealing, taping, etc. The total cost estimates should include

the price of the components, the thermal blanket as well as the cost of extending it, labor cost to install the system and changing the interior design of the existing greenhouse. Estimates for the installation of a complete system range from $15 to $25 per m^2.

(viii) Typical Blanket Systems

With several systems the thermal curtain moves either across the short dimension of the greenhouse or along the long dimension.

Illustrated in Figure 3 is a system used in clear span freestanding houses where crops are not supported from the trusswork. Individual small pulleys support the blanketing material from powered cables which are spaced 3 to 4 m apart. Static lines between the drive cables also support the curtain, which is normally stored in the north wall. In wide houses over 12 m wide, the curtain is drawn from each side toward the middle. A 15 cm inflated polyethylene tube forms an adequate seal where the two moving curtains intersect at the center of the greenhouse.

In the classic Dutch house, curtains are moved above the framework used for supporting the crop. The curtain is moved from one gutter to the next or from truss to truss. The leading edge of the curtain is pulled by a pipe drawn by cables spaced approximately 3 m apart. The blanketing material is supported by monofilament plastic lines approximately 60 cm on center (Figures 4 and 7).

Some systems use monofilament lines over the blankets to help keep it in place when the mechanism withdraws the blanket. This sytsem is commonly used in Europe for shading with porous translucent materials such as Thermoshade, Terylene, or Reemay or with non-porous materials such as vinyl or polyethylene.

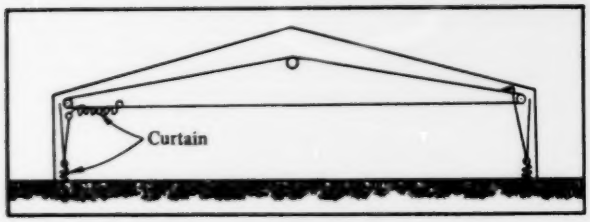


Figure 3: A curtain system for clear span greenhouse

Greenhouse construction may have an important influence on the type of thermal curtain system to install (Figure 5). Typically the thermal blanket will be stored in the peak and will move to the gutters. The advantages of this system are that a large air volume is maintained, and a fanjet system with polytube can be located underneath the material. This system conserves less energy than a number of others because two seals are required per house, and because there is more surface for heat transfer per greenhouse floor space.

In some greenhouses – in particular curved rafter polyethylene or fibreglass covered greenhouses – horizontal systems which move the length of the building are used. These systems can be cable operated or supported with aluminum track and moveable low friction pulleys (Figure 6). The system stores all the material at the end of the greenhouse which overcomes the problem of storage along the inward sloping wall. Another commercial system utilizes linear motors which operate within an aluminum track instead of cable drive.

5. Permanent Sidewall and Gable Insulation

Fiberglass batts, styrofoam sheeting or blown polyurethane can be applied to insulate sidewalls and gable ends up to the height of raised beds. Where perimeter heat lines exist, apply the insulation behind the lines. A reflective paint or lining will be helpful in redirecting heat back into the greenhouse. Flammability and durability of any insulation material should be considered before installation.

On older greenhouses with a block or cement foundation, it is recommended that the insulation be placed on the outside. This allows the mass of the sidewall to absorb solar heat during the day and reradiate it at night.

Many Ontario growers have permanently insulated their entire northern exposed sidewalls and gable ends. This greatly reduces infiltration and warms up the traditionally cold end or side of the house. Try to have the insulation a color such as white to reflect winter sunlight back into the crop. We have not observed any detrimental effects on any crop with this system.

6. Insulation of gutter

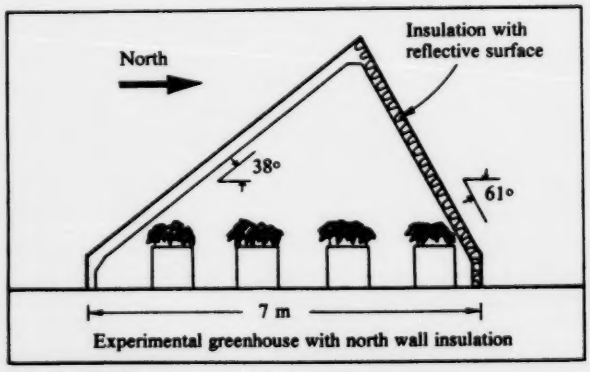
Increasing the insulation value for the greenhouse structure could also include the gutter. However, two factors have to be considered. Insulation of the gutter will mean that snow can not be melted easily by turning on the heat lines in the greenhouse or below the gutter. Moreover gutters, because of cold temperature, are excellent dehumidifiers in a greenhouse. High relative humidities are not uncommon in well insulated greenhouses, and have to be weighed against fuel consumption. Excess water condensate from the gutter is usually removed through drip gutters located below the bottom of the gutter. If thermal curtains are used the formation of ice on the gutters and drip gutters can cause problems, provided the curtain material is located close to the gutter. A solution is presented in Figure 7, where a thermal curtain is used in combination with a shielded gutter. Provision is made for water condensation to take place on the bottom of the gutter. Water is removed through the use of two drip gutters per gutter. The thermal curtain abuts the shielding preventing the possibility of freezing.

7. Vent Sealer

Roof and sidewall vents can be sealed effectively with a gasket material that is stapled and glued to the vent frame (Figure 8). It can be used on wooden or metal frames and acts similar to a spongy weather stripping.

8. Brace Experimental Greenhouse

The Brace designed greenhouse is currently being investigated from an energy conservation standpoint and production efficiency at different locations. Commercial adaptability is limited.



Experimental greenhouse with north wall insulation

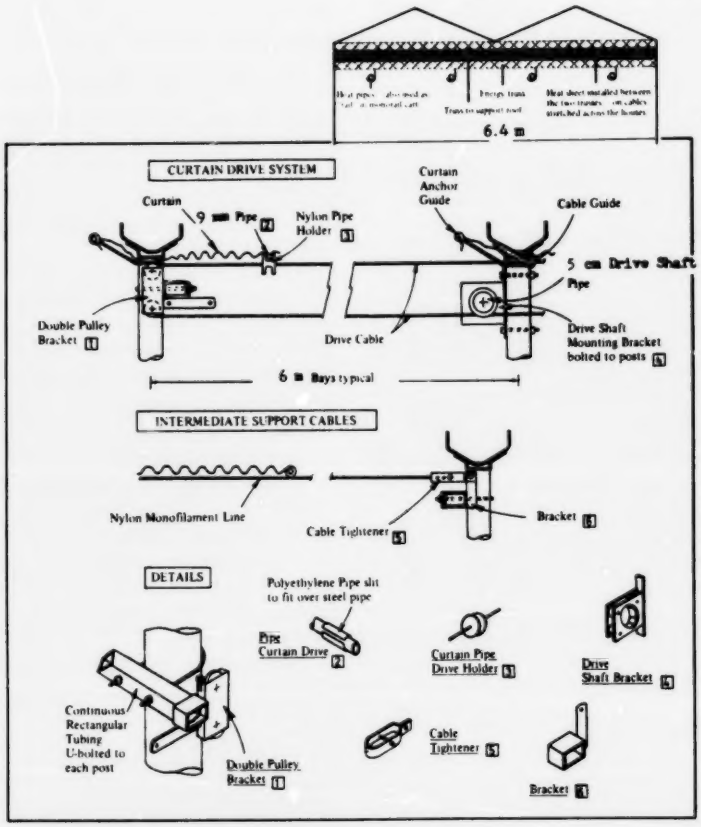


Figure 4: Curtain system for gutter connected greenhouses

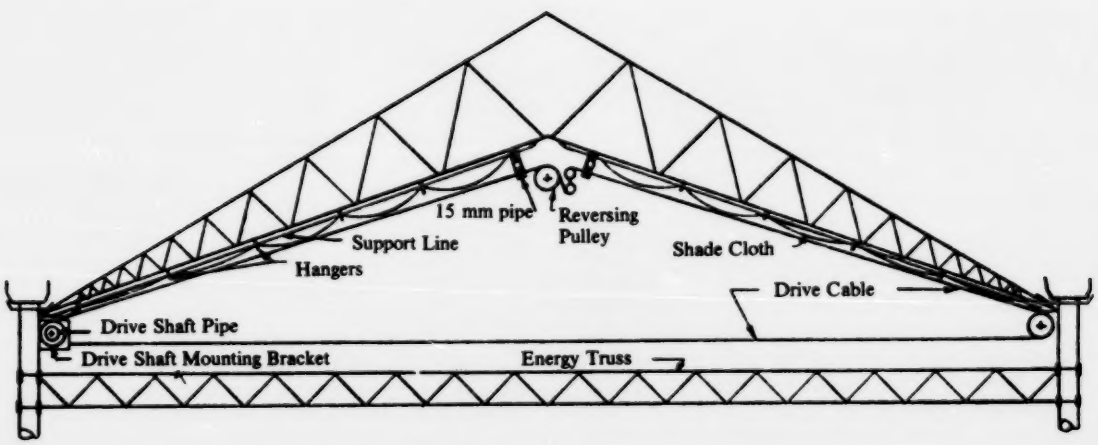


Figure 5: Thermal blanket arrangement for scissor truss greenhouse

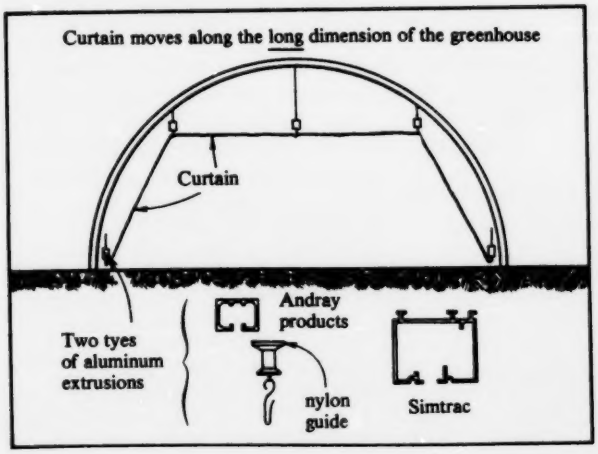


Figure 6: Aluminum track system for curved roof greenhouses

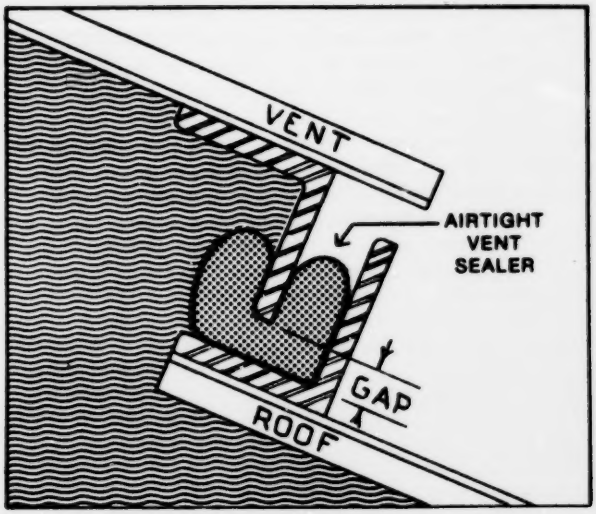


Figure 8: Schematic diagram of application of vent sealer

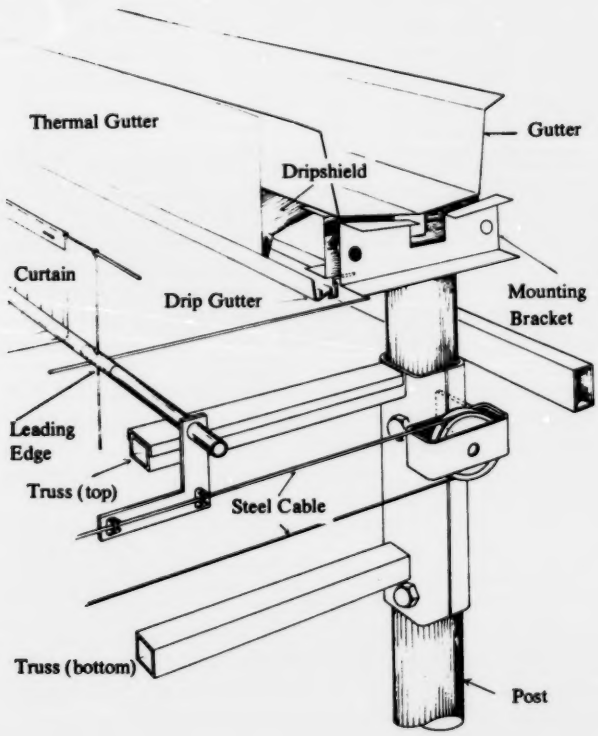


Figure 7: Schematic drawing of thermal gutter and moveable curtain

B. Lowering the Temperature Differential

1. Lower temperature and alternative crops

Lowering the greenhouse temperature will reduce the differential between inside and outside temperatures and thus reduce fuel consumption (Table 7).

The lower the average outside temperature, the smaller the relative savings will be from lowering the temperature. The actual amount of fuel saved can still be significant (Table 8).

Reduced air temperatures may have negative effects such as increased time to maturity and reduced quality. Cultivars have been developed for many crops which are more tolerant to lower-than-traditional temperatures. Unfortunately not all of these cultivars have been fully tested and growers should use them on a trial basis.

High fuel costs have resulted in the emphasis being placed on alternative crops which can be grown at lower temperatures than roses or cucumbers. Lettuce, radish, celery or gerbera are examples of such crops. The major concern is the development of markets for these crops. Lettuce for example is a fuel efficient crop in the greenhouse but underdeveloped marketing channels and uncertain prices can reduce its profitability.

Table 8. Percent reduction in fuel use when greenhouse tempertures are lowered on a 24-hour basis

	Inside Greenhouse Temperature (°C) Reduction from A to B						
A	20	20	18	18	16	16	16
	to	to	to	to	to	to	to
B	18	16	16	14	14	12	10
Average Outside Temperature (°C)	**%**	**%**	**%**	**%**	**%**	**%**	**%**
-9	7	14	7	15	8	16	24
-6	8	15	8	17	9	18	27
-3	9	17	9	19	10	21	31
0	10	20	11	22	12	25	37
3	12	24	13	26	15	31	46
6	14	29	17	33	20	40	60
9	18	36	22	44	29	57	86

2. Split night temperatures

This concept has received widespread research input in recent years. The theory is to maintain normal night temperatures until approximately midnight and then lower the temperature by at least 5°C until morning. Studies have shown that crop response varies widely depending on variety, stage of development and duration of reduced temperature. Unfortunately no general recommendations are available, but the technique appears to be of value to chrysanthemums when the split night temperature treatment is applied after buds have reached the size of a pea and the temperatures maintained at 10°C (18.00 - 24.00 hr.) and 16°C (24.00 - 06.00 hr.). A split night regime is being tested for tomatoes and looks promising.

3. Closing during winter

In the section on calculating heat loss, the average monthly fuel consumption was presented in Table 4. From these data it is obvious that substantial energy savings are possible by not operating during the coldest months of the year (up to 50%). This is not possible for perennial ornamental crops and costs must be balanced against reduced returns for seasonal vegetable production. If the greenhouse is closed in winter, heavy snow loads should be removed to prevent structural damage. Water pipes must also be protected from freezing.

4. Preheat irrigation water

If cool water is used to irrigate plants, that water will be raised to greenhouse air temperature by extracting heat from the plants and greenhouse atmosphere. It is a better horticultural practice to irrigate with warm water so that no cold shock is given to the plants. Preheating is recommended as the same amount of energy is required to warm the water by preheating as is used by extraction from the greenhouse environment. This practice is particularly useful if a condenser or some form of waste heat can be used to heat the water. Most systems which utilize waste heat will require some type of cistern storage.

C. Optimizing Fuel Conversion Efficiency

1. Combustion efficiency

The basic principle of a heating system is the conversion of a fuel (chemical energy) into sensible heat in order to compensate for the heat loss from a building or structure. In a boiler, fuel is combined with air in a combustion process through which heat is produced. This heat is contained in the flue-gases in the form of sensible heat (85 to 90%) with the remainder being latent heat (water vapor). The control and operation of a boiler is directed to the regulation and maintenance of a proper fuel-to-air ratio. This ratio of fuel and air is very important, as it directly affects the efficiency of the burner. Not enough air results in incomplete combustion and large amounts of soot. An excess of air will cause lower flue gas temperatures and consequently a lower rate of heat transfer into the waterside of the boiler. The combustion efficiency of a boiler is determined by measuring several parameters, such as temperature of incoming combustion air as well as the temperature and carbon dioxide level of the flue gases. The smaller the difference between the flue gas and combustion air temperatures, the higher the combustion efficiency.

The heat transfer from flue gases into the waterside of the boiler is also important. A clean surface, both on the fire, as well as on the waterside is necessary for rapid heat transfer. Cleaning accumulated dirt and soot from the fire tubes on a regular basis is essential. In addition, water should be treated to prevent pitting and scale build-up. A poor heat transfer from the flue gases into the water leads to higher flue gas temperatures and thus a lower combustion efficiency.

Regular inspection, cleaning of boiler and possible adjustment of fuel-air ratio are normal requirements to obtain optimum boiler combustion efficiency.

2. Heat distribution system

A heating system not only must have sufficient capacity to offset heat losses from the greenhouse but must also provide a constant, uniformly distributed temperature. The location of heat exchange surfaces or unit heaters is critical. Three primary heating systems used in Ontario greenhouses are central boiler with a network of pipes, forced hot air heaters and infrared heating.

(i) Central heating

The pipes contain either hot water or steam. Both steam and hot water systems can provide good control and uniformity of the temperature through staged control. An advantage of a central boiler system is that the combustion efficiency can be high (80 to 85%) and residual heat in the pipe network can provide some security in cases of boiler failure. Overall seasonal efficiency is considered to be between 70 to 75%. The versatility of a hot water heating system should be considered. A hot water heating system can provide both soil and crop heating which can be of great benefit to some crops. Crop heating may reduce temperature stratification in the greenhouse as well as radiative heat losses through the glazing material, resulting in substantial savings in heating costs (10 to 15%).

(ii) Forced hot air heaters

Several types of gas-fired hot air unit heaters are marketed at relatively low cost. Air circulation (eg. fan jet and polytubes) are essential for better temperature distribution. For proper operation of unit heaters, sufficient fresh air (one cm^2 of opening for each 100 W of capacity of burner) must be provided. Despite inexpensive installation costs very few operators (except bedding plant growers) have unit heaters in their greenhouses. The three major drawbacks are:

(a) relatively poor combustion efficiency for the standard atmospheric burners. Combustion efficiency is usually in the 70 to 80% range with high "stand still" losses. Overall seasonal efficiency is between 60 and 70%.

(b) poor temperature distribution within the greenhouse; circulation tubes do help but usually there is a cold area where the burner is located; and

(c) the danger that gases from incomplete combustion or raw fuel escape into the greenhouse.

(iii) Infrared (IR) heating

The concept of many small burners within a distribution system is accomplished by an IR system. The major differences between this and a central boiler system is that flue gases are drawn through the piping system rather than forced through the primary heat exchanger (boiler). Exhaust temperatures of the flue gases can be very low (50 to 70°C) resulting in a relatively high combustion efficiency of the burners (85 to 90%). Due to negligible "stand still" losses or transportation losses, the seasonal efficiency is very high (80 to 85%). Expected energy savings of IR heating relative to a central boiler system with overhead heating lines will be around 20 to 25%. Research is being conducted to determine whether leaf temperatures are warmer than air temperatures, as claimed by manufacturers.

Poor temperature distribution in the horizontal plane, light loss due to overhead equipment, the limited number of fuels which can be used (natural gas or propane), and lack of

flexibility of system (no soil pasteurization possible and the requirement of a high greenhouse) are major drawbacks. IR-heating should be considered for gutter connected ranges with gutter height of at least 3.0 m.

3. Preheating of combustion air

The efficiency of a boiler can be improved by increasing the temperature of the combustion air. Often warm air is located in the top of the boiler room and this air can be forced down by means of a small fan and used in the combustion process. Another technique would be to use a heat exchanger around the stack to warm up combustion air.

4. Transportation losses

Loss of heat from a bare steam or hot water pipe varies with the difference between the pipe temperature (T_p) and that of the surrounding air (Ta) and with the type of pipe (Table 9). The higher the difference in temperature, the greater the heat loss.

Table 9. Heat loss (Watt/metre) from two types of pipe in relation to size, material, and temperature differential, ΔT, (T_p-T_a)

ΔT	Watt per metre of pipe		
(°C)	Steel (51 mm diameter)	Steel (102 mm diameter)	Tubylene (25 mm diameter)
10	15	27	6
20	34	61	14
30	55	99	24
40	77	138	35
50	101	181	46
60	128	230	–
70	156	280	–
80	185	332	–

Pipe headers are often located in the center of the greenhouse and pass through service buildings. Relatively large amounts of heat are given off by these pipes, resulting in unnecessary heat losses (transportation losses) and creating a warmer area in the greenhouse. When the number of heating hours in a day and the number of days in a year and the length of uninsulated pipes are multiplied, an enormously large amount of heat is lost in an area where it is not desired. Insulation (about 2.5 cm thick) material for a 15 cm pipe costs about $8 per linear meter.

5. Stand still losses

Heat is lost from the boiler on a continuous basis, both as external losses through the boiler wall and as internal heat losses through the stack. Sufficient boiler insulation will prevent the external losses. Dampers in the stack, which will prevent internal losses are presently available, however, they have not received CSA approval (as of 1982).

6. Economizers (Condensers)

An economizer or condenser, can be described as a heat exchanger which is placed between the boiler and the chimney in order to recover the latent heat (as water vapor) from the flue gases. The basic principle is that by reducing the temperature of flue gases sufficiently, water condensation will take place and the heat of vaporization (or latent heat) becomes available. Flue gas temperature must be reduced to about 50 to 55°C in the condenser to make the system effective. This latent heat is extracted by the economizer and can provide up to 12% of the total fuel energy input. The installation of an economizer is only useful when low temperature water is required for such purposes as heating or preheating of irrigation water. The application of economizers on conventional boilers is restricted, since only fuels with a low sulfur content can be used; sulfuric acid, formed following combustion of high sulfur fuels, corrodes the economizer. Ontario regulations require minimum stack temperatures of 150°C in conventional boilers with positive exhaust systems.

7. Retarders (Turbulators)

The efficiency of fire-tube boilers can be improved by the use of retarders (turbolators). The retarders are usually steel coils which are placed in the tubes of a boiler. The presence of these coils increases the time that flue gases remain in the boiler, as it retards or delays the movement of gases into the stack. This consquently allows more time for heat to be exchanged and thus reduces stack temperature. Not every boiler and/or burner combination is suitable for the use of retarders.

8. Location of heat source

Because warm air naturally rises, it is efficient to have the heat pipes located as low as possible. With crops grown in ground beds such as tomatoes, roses and chrysanthemums, the primary heating lines are best located either between rows or on the outside of the beds. Natural convection will ensure that the crop foliage will stay much drier and therefore will have less disease. With tables or bench crops, bottom heat is recommended. This location results in lower radiative heat losses from the greenhouse and considerably less temperature stratification. Energy savings of 10 to 20% are claimed if compared to overhead heating.

Because of snow loading, a secondary heating system located under the gutters is recommended. This can be activated by a separate thermostat or snow monitor.

9. Soil heating

The soil temperature can be raised through the use of heating lines (polyethylene or butylene) through which warm water flows. As soon as the soil has reached a higher temperature than that of ambient it will provide a constant heat source and a uniform distribution.

Soil heating is difficult to regulate in a short period as the soil termperature reacts very slowly to an increased heat supply. Heating pipes should not become too warm as the soil around the pipes may dry out and will act as an insulation layer. An even temperature distribution near the soil surface should be the objective of soil warming.

Heat conductivity of a soil is difficult to estimate. It is dependent on the type of soil, amount of organic matter, moisture content, and bulk density. In Europe, spacing of heating tubes has been recommended on the basis of trial and error; a standard recommendation is that tubes should be placed at a depth of about 45 to 60 cm and on 60 to 90 cm centers.

The tubes are made of black, flexible, heat resistant, butylene or polyethylene, usually 2.5 cm in diameter. The water temperature within the tubes usually does not exceed 35°C especially after the soil surface has reached a temperature of 20°C.

Soil heating is being used in Ontario commercially on crops such as chrysanthemums (winter), poinsettias, tomatoes and cucumbers.

10. Soil pasteurization

The conventional method of soil pasteurization by top steaming requires about 60 kg of steam/m^2 for complete pasteurization, assuming a soil depth of 60 cm. Top

steaming is often referred to as the Thomas method. For a boiler with a combustion efficiency of 80% about 2 x 10^8 J/m^2 input is needed. This would be equivalent to 51,000 L of No. 2 oil or 54,000 m^3 of natural gas per hectare. This type of steaming is often done for vegetables, roses and carnations, where a deep layer of soil has to be pasteurized and sometimes (for roses and carnations) must last for several years. A shallower pasteurization is performed for certain other crops, such as chrysanthemums and only one-third to one-half of the above-mentioned energy consumption is required.

Pasteurization through tiles is about 20 to 30% more energy efficient than the Thomas method. Large ranges are better adapted to this type of procedure, especially those used for seasonal production.

Soil fumigation for the control of nematodes or for soil sterilization has become a standard practice for many growers (see OMAF Factsheet, *Soil Fumigants*, Agdex 606). Although 1982 costs of soil fumigation are approximately 1/3-1/4 those for soil pasteurization by steaming, the effectivenss may often be less. There is a tendency to saturate or overdose certain parts of the soil and undertreat others.

For batch steaming of soil such as in a soil wagon, the use of aerated steam is recommended rather than straight steam. A theoretical calculation indicates that one cubic metre of a 1:1:1 mix (peat, perlite, soil) requires about 148 MJ for aerated steaming. This represents a 30% savings of energy and leaves the soil in a better physical and biological condition.

D. Reducing Energy Input Per Unit Product

1. Lighting

Although electric heating is not currently price competitive with natural gas or oil for greenhouses, many operators use some form of supplementary lighting. This lighting is necessary for desired plant responses but, in addition, all electrical energy going into greenhouse lighting is converted to either light or heat. Bulb types differ in their conversion ability, e.g., high pressure sodium is approximately 25% efficient while incandescent is only 7%. The remainder of the input (75% or 93% resp.) is converted to heat.

When lighting is used to control photoperiod (e.g. chrysanthemums), cyclic lighting can be considered. Instead of lights being on constantly for four hours to break up the dark period, the cyclic lighting technique utilizes lights for only six of every 30 minutes. Length of supplemental lighting period depends on season. Sufficient light-intensity (at least 100 lux) must be maintained at plant level for this technique to be effective.

2. Thermostats

Accuracy of thermostats should be checked periodically by comparison with a good quality precise thermometer. Thermostats should be accurate to within one degree. The thermostat should control the temperature with very little fluctuation since wide variations in temperature will increase fuel consumption.

Thermostats should be shielded from direct exposure to the sun, and placed in an aspirated box at crop level. The aspirated box will draw greenhouse air past the thermostat, providing an accurate reading of the greenhouse air temperature. The air should be drawn past the thermostat rather than blown across since heat produced by the fan may cause a false air temperature to be sensed by the thermostat.

3. Fans

Greenhouse exhaust fans are difficult to seal tightly when the fan is shut off. This seal should prevent the air from exchanging through the louvered closures that are on most fans.

Instead of using the louvered closures, it is recommended that the fans have a fiberglass covered frame that fits snugly over the outside perimeter of the fan box. The cover is made of aluminum angle iron and is attached (and pivots) at the top edge of the fan box. The aluminum angle iron sides are extended past the pivot point and connect with a counterweight (metal pipe, etc). The balance of the closure system is designed to close automatically and provide a tight seal when the fan is shut off. On the other hand, when the fan goes on, the closure swings out to allow easy passage for the exhausted air. It is prevented from opening too far by small chains attached at the bottom.

As a note of warning, the system is very simple but care must be taken in the initial construction so as not to cause damage to the fan motor. It is important to have little or no resistance when the cover opens. It is also important to allow the cover to open enough so that the flow of air is not restricted. Either condition could cause excessive static pressures on the fan which it may not be designed for and motor damage could result. As long as care is taken in the counterbalancing and the chain adjustment, there should not be any problems. In addition, the metal sidewalls of the fans can be insulated with either sheets of polystyrene or blown polyurethane.

Recent changes in electrical motor technology have resulted in motors which are as much as 25% more efficient in electric conversion. These motors are particularly cost-effective in situations of prolonged use. Circulating and ventilating fans are prime candidates for replacement with energy efficient motors.

4. Increasing productivity per unit area

Energy conservation can be viewed as both reducing the amount of fuel used per m^2 of greenhouse space as well as reducing fossil fuel input per unit of product sold. The latter situation can be achieved through the use of management techniques such as supplemental carbon dioxide and lighting, moveable benches, soilless growing and potting media and multiple level shelving. These techniques are dealt with in detail in other publications, but when considering the economics of utilizing one of these methods, the grower should calculate the effect of reducing unit energy costs.

5. Relative humidity

High moisture levels in a greenhouse increase fuel consumption in several ways. Evaporation of free water in the greenhouse or from plant surfaces requires heat taken from the greenhouse air. Cold surfaces in the greenhouse (gutter, glazing material) will condense water vapor at a rate depending on its surface temperature, air movement and relative humidity. Excessive relative humidity is generally controlled by venting the warm humid air from the greenhouse and replacing it with cool dry air. This air must be heated to the required greenhouse temperature thus creating a heat demand. Management techniques such as trickle irrigation, soil drainage or mulching should be employed to reduce both free water and thus high humidity. Extensive work is being done with dehumidifiers which are using the warm exhaust air to heat up the incoming cold air.

6. Microprocessors – computers

European experience has shown that microprocessors can be used to control the greenhouse climate. The advantages of using this equipment include energy conservation, reduced labor input and provision of horticulturally optimum growing conditions. The microprocessor combines inside and outside climatic information and based on complex mathematical formulae can control the greenhouse temperature to a precise but flexible set point. Automatic night temperature set back, control of split night temperature, variable day temperature dependent on solar radiation are examples of energy conservation potential with these units. The high cost of controllers cannot be justified solely on energy savings except in a very large operation.

Several factors must be considered before purchasing this type of sophisticated equipment. Since the greenhouse environment is not well suited to electronic devices, a suitable location in a greenhouse office or packing area must be used to situate the main control unit. The supplier should be available for service and maintenance of the equipment. Interfacing with the current controls may be difficult or impossible and new heating and cooling control systems may be required before the computer can operate properly.

COST ANALYSIS OF CONSERVATION TECHNIQUES

There are many energy conservation techniques that a grower may use. Not all of these can be considered economic or applicable in all situations. Growers must determine the cost of an installation versus the benefits such as fuel savings or increased/decreased production, before a particular technique is implemented. The principle factors to consider are capital costs, operating costs, interest charges, required amortization period and effects, if any on production. On the positive side, fuel savings and projected fuel price increases (Figure 1) must be weighed against cost.

Each grower should determine the annual costs of a given technique for his greenhouse and then estimate the possible fuel savings. These costs vary widely among growers and therefore general recommendations are not possible. Information has been summarized (Table 10) to assist growers in evaluating a conservation technique. The following will serve to illustrate how the information in Table 10 can be used. First, assume a technique will cost $\$4/m^2$ year. Next locate this value in each column of the table and draw a line as shown. In this circumstance, any of the conditions noted below the line are profitable and those above the line should be avoided.

Example A

A grower is considering the installation of a thermal blanket system in an existing greenhouse.

Step 1 Calculate energy cost

The total energy used per unit area must be determined before any cost benefit analysis can be conducted. An average value is 75 L of No. 2 oil/m^2/year if the greenhouse is operated year-round at 17°C minimum night temperature. The consumption is multiplied by the current cost to give the fuel cost per unit area.

Step 2 Calculate energy savings

The energy savings from a thermal blanket system will vary depending on material, installation and usage. The general average savings which has been reported by commercial growers and researchers is 30%. The energy cost is multiplied by the savings to find the energy savings per unit area.

Step 3 Calculate annual cost

1. Capital cost divided by amortization period
2. Operating costs (electricity, repairs, maintenance)
3. Interest charges (cost of borrowing capital)

Step 4 Consult table

In this example, fuel consumption of 75 L/m^2/year and an energy savings of 30% have been used. If the current fuel price is 25¢/L, then $\$5.62/m^2$ will be saved. If the annual cost of the thermal blanket is less than $\$5.62/m^2$, then it will be profitable to install the blanket. If fuel prices rise to 35¢/L, it will be profitable to install the same system if the annual cost is as high as $\$7.88/m^2$.

If the fuel consumption were only 50 L/m^2/year at a cost of 25¢/L and the same 30% fuel savings, then the thermal blanket system would not be cost effective unless the annual costs were less than $\$3.75/m^2$/year.

Example B

A grower is considering the installation of a low intensity infrared heating system in a greenhouse.

Step 1 Calculate energy costs as in Example A

Step 2 Calculate energy savings

Reports of energy savings which are achievable with an infrared heating system vary significantly. The percentage saved is dependent on efficiency of the current heating system, type of glazing and external climatic conditions. A general average value is 25%.

Step 3 Calculate annual costs

The capital installation costs vary depending on size of operation and have risen steadily over the last two years. The amortization period should be equivalent to the expected life of the system which is usually considered to be 10 years. Current (1982) estimated annual costs are $\$6.25/m^2$ for the system only.

Step 4 Consult table

If the fuel savings are 25% on a consumption of 75 L/m^2 and fuel costs of 20¢/L then the fuel savings amount to $\$3.75/m^2$. The net revenue would be:

Energy savings	–	Annual cost	=	Net revenue
$3.75	–	$6.25	=	$-\$2.50/m^2$

The above example considers the case of the IR-heating system being used as a retrofitting technique. In the case of no heating system being installed (eg. new greenhouse), only the additional annual costs should be calculated. An estimate of the annual costs in excess of a conventional heating sytem is about $\$1.75/m^2$. The net revenue then becomes:

Energy savings	–	Annual cost	=	Net revenue
$3.75	–	$1.75	=	$+\$2.00/m^2$

Table 10. Volume and value of energy saved per m^2

Energy Saving (%)

Fuel consumption in L/m^2 No. 2 oil	5	10	15	20	25	30	35	40	Fuel price (¢/L)
		.25	.50	.75	1.00	1.25	1.50	1.75	2.00	20
25	1.25	.31	.62	.94	1.25	1.56	1.88	2.19	2.50	25
		.38	.75	1.12	1.50	1.88	2.25	2.63	3.00	30
		.44	.88	1.31	1.75	2.19	2.62	3.06	3.50	35
		.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	20
50	2.50	.62	1.25	1.88	2.50	3.12	3.75	4.37	5.00	25
		.75	1.50	2.25	3.00	3.75	4.50	5.25	6.00	30
		.88	1.75	2.62	3.50	4.38	5.25	6.13	7.00	35
		.75	1.50	2.25	3.00	3.75	4.50	5.25	6.00	20
75	3.75	.94	1.88	2.82	3.75	4.69	5.62	6.56	7.50	25
		1.12	2.25	3.37	4.50	5.62	6.75	7.88	9.00	30
		1.31	2.62	3.93	5.25	6.55	7.88	9.19	10.50	35
		1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	20
100	5.0	1.25	2.50	3.75	5.00	6.25	7.50	8.75	10.00	25
		1.50	3.00	4.50	6.00	7.50	9.00	10.50	12.00	30
		1.75	3.50	5.25	7.00	8.75	10.50	12.25	14.00	35

In this case, the IR-heating system provides a net saving.

Factors other than capital costs must also be considered when determining the cost effectiveness of energy conservation. Most alterations to a greenhouse structure will result in a change in greenhouse environment. If yield is likely to be reduced because of the energy saving technique employed, this fact should be included in the economic consideration. The most important changes that typically occur are in light losses and in relative humidity. The energy conservation device used may also provide beneficial side effects, such as crop shading achieved by a thermal blanket during the summer.

ALTERNATE HEAT SOURCES

Heat Pumps

Heat pumps have been available since the 1950's but high fossil fuel prices have created recent widespread interest. The principle of operation is similar to refrigeration units where there is an indoor and an outdoor component. In the heat pump, heat is exchanged through the phase changes (liquid to gas and visa versa) of a refrigerant, (such as freon), by means of a fluid. The liquid form is piped from the interior of a building to the outdoors where it is expanded in an evaporator and changed from a liquid to a gas. The energy needed to change from liquid to gas (heat of vaporization) is extracted from the surrounding air. A compressor then circulates the gas back to inside the building where it condenses back to a liquid giving up the heat of vaporization and warming the interior air. Most heat pumps use hydro for their source of power.

Industrial heat pump designs are available that will provide up to approximately 21,000 MJ per hour in a single package unit. The source of this heat can be any water supply ranging from ground water at 4 to 10°C to industrial waste waters at 40°C or higher; the higher the temperature of the water, the higher the efficiency of the heat pump.

Industrial applications of heat pumps include provision of hot water for space heating, for pre-heating boiler feed water and for industrial process water (up to 105°C). Depending upon the initial source water temperatures, the thermal output of a heat pump can typically be two to six times the thermal equivalent of the electrical energy input. In Ontario, electrical energy is relatively inexpensive, typically about 3.5¢ kWh, equivalent to 3.6 MJ. Cost of electrical energy is, therefore, approximately 1¢ per MJ. Heating of greenhouses presents a difficult, but not necessarily insurmountable problem for heat pump technology. Capital costs of heat pumps generally dictate year-round service. The application of the heat pump for summer cooling may help to offset the high costs. The highly seasonal requirements, daily fluctuations in heat demand of a greenhouse and availability of electrical service can be prohibitive factors. The first two concerns may be overcome, however, by addition of thermal storage and appropriate optimization of the heat pump rated capacity to reduce total capital costs.

Solar

By its basic nature, the greenhouse performs as a collector or solar energy. Solar radiation passes through the glazing material and is trapped inside the structure. During bright days, even in winter, the amount of solar energy is in excess of energy requirements needed for maintaining desirable temperatures and must be expelled through ventilation. Unfortunately solar radiation is extremely unpredictable during the winter months in Canada and therefore efficient storage systems must be developed for cloudy days. In addition, during most of the peak heat demand periods, there is insufficient solar radiation to maintain required temperatures for even one night following a sunny day.

Neither active nor passive solar heating is feasible as the sole source of heating a greenhouse in Canada unless long-term storage systems are developed. On an annual basis there is about $1\frac{1}{2}$ times as much solar radiation received at a horizontal surface compared to the heat requirements of a greenhouse on an equivalent surface area. Solar can assist in reducing the consumption of fossil fuels but currently very few systems have widespread use due to lack of economic viability or practicability.

Passive solar heating has been shown to be suitable for small scale greenhouses but extension to full size commercial units has been restricted. Passive solar designs generally incorporate a high degree of insulation which reduces the overall heat demand of the greenhouse, thus the passive solar heating provides a larger percentage of the heat requirement. Most passive solar greenhouses significantly reduce the amount of light available to the crop because of the large surfaces insulated. This is not critical for the production of crops which have a low light requirement, but for the majority of crops grown in greenhouses, the light loss results in reduced yield which usually more than offsets the energy savings. Current research is aimed at the recovery of latent and sensible heat from the greenhouse air. This heat is to be used either to preheat incoming ventilation air or to be stored for nighttime heating.

Active solar heating encompasses mechanical systems for external collection of heat. This method usually includes external solar panels or collectors which continually collect heat during sunny periods. These collectors can be air and/or water systems. Essentially the heat is transferred from the collector surface to the transport medium (air or water) and this is conducted to a storage facility. Current estimate of the efficiency of this system is that a 1:1 ratio of collector surface to greenhouse ground area will provide 50% of the heat requirements of a standard double polyethylene greenhouse fitted with thermal blankets. Cost of collectors varies from \$30-300/m^2. Efficiency of collectors varies with design and some models collect practically no heat. Twice as much land area as collector area is required to set up most collectors and this becomes a consideration in retrofitting a greenhouse in confined areas.

Industrial Waste Heat

Heat is the by-product of many industrial processes. In the past, the heat rejected from manufacturing plants, electricity generating stations or other sources was considered low grade heat of an unreliable supply. High fossil fuel costs have produced a desire to increase efficiency of fuel usage and has led to a re-examination of these sources of heat. About 10 major research projects are underway in Canada which utilize low grade heat to maintain greenhouse temperatures. The methods of heat distribution in the greenhouse are radically different than the pipe heat exchange systems currently used. These research projects have demonstrated that temperatures of 15°C can be

maintained in the greenhouse with water at a temperature of 30 to 40°C.

There are many opportunities in Ontario to utilize waste or reject heat for greenhouse production, but several variables must be considered. These would include reliability of source, cost of heat, location of source in relation to market, desirable soil type, labor force and acceptable climate. Many of the schemes which are promoted may not be economically viable and each system must be examined on its own merits. Wherever possible, advantage should be taken of this valuable resource.

Total Energy

In situations where demands for heat coincide with the need for electricity, it may be worthwhile to look at a Total Energy Unit (TEU). Such units can be compared to electric generators with the exception that the heat produced is being extracted through heat exchangers. The energy source used for a TEU can be natural gas, propane or diesel fuel.

There are several TEU models on the market in Europe, which have the following energy conversions:

electricity	30%
usuable heat	50%
waste heat	20%

These provide an overall efficiency of 80%. The newest models claim efficiencies as high as 95%. There are several questions which have to be addressed when examining the economic feasibility of TEU's:

- When the TEU is in operation, is there a use for the heat and electricity generated at the same time? The ratio of heat generated and electricity produced is fairly constant. If electricity for supplemental lighting on a 24 hour basis is required, a basic knowledge is needed of the heat demand during the nighttime as well as during the daytime for the greenhouse range.
- Is a heat distribution system for the heat generated available? A hot water heating system is necessary for this.
- What are the economics of such a system? Important to the pricing of the system are costs of natural gas versus electricity, the installation, depreciation and operation costs of a TEU.

At this time, these sytems do not appear to be practical in Ontario.

Biomass (alcohol)

Lignocellulose, which is found in cell material of plants, can be converted to fuel alcohol (ethanol or methanol) or natural gas. The conversion involves rather complicated technology and for economic reasons, must be done on a large scale. The conversion factors are presented in Table 11.

Table 11. Potential of alcohol and energy from lignocellulose[1/]

Fuel	Production equivalent/ha/year		
	L	m^3	GJ[2/]
Ethanol	5400	–	51.7
Methanol	650	–	4.7
Natural gas (methane)	–	3500	56.4

1/ Produced by hydrolysis – wet oxidation – fermentation, assuming 22.5 tonnes oven-dried lignocellulosic material per hectare per year. Source: Dr. D.L. Brink, Forest Products Laboratory, University of California

2/ 1 GJ (gigajoule) = 948,000 BTU

Wood

There is a considerable interest in burning wood chips and shavings as a source of heat, in particular where the supply of fossil fuels has been restricted or is naturally limited. There are about seven greenhouse operations currently using wood chips as a source of fuel in North America.

It is difficult to predict an equivalent fuel output for wood since it depends on moisture content and density. One cord of wood is approximately equal to 500 L of No. 6 oil. One tonne of wood chips with a 50% moisture content is approximately equal to 250 L of No. 6 oil.

Two main problems associated with burning wood chips are the high cost of installing a completely new heating plant and a reliable source of wood chips. The supply and storage of the material is a problem since up to 20 tonnes of chips can be burned in one night to heat one hectare.

Environmental considerations look promising since the combustion is at 1600°C and therefore complete. In addition, 50% of a tree is considered waste in the lumber industry and the chips represent a renewable resource. It is difficult to landfill the waste material.

A demonstration project using waste wood as a source of heat has been started in Ontario for a 0.5 hectare greenhouse operation.

Coal

Comparative fuel costs (Table 6) indicate that coal has become a viable alternative for greenhouse operators.

The economic problems associated with the use of coal as a heat source are related to the high capital investment required for storage, handling and burning. It is these main factors that limit the practicability of coal for Ontario greenhouse growers. One additional consideration is that Ontario relies on imports of coal from the United States, so there is no domestic control over cost or supply.

Coal is used by some growers as a standby for emergency situations usually utilizing old equipment.

Reused Oil

Old crankcase oil, etc, has been used by a few growers with the cost approaching 25% of that for new oil. It can either be collected or delivered. Experience at this point is limited but growers should be cautious of corrosive properties and air pollutants. Further, availability may become a limiting factor as the demand for old oil increases.

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CONVERSION FACTORS

When you know	Multiply by	To find	Reciprocal
LENGTH			
inches	25.4	millimetres (mm)	0.0394
feet	30.5	centimetres (cm)	0.0328
yards	0.914	metres (m)	1.09
miles	1.61	kilometres (km)	0.621
micron	0.000001	metres (m)	1,000,000
AREA			
square inches	6.45	square centimetres (cm^2)	0.155
square feet	0.0929	square metres (m^2)	10.8
square yards	0.836	square metres (m^2)	1.20
acres	0.405	hectares (ha)	2.47
VOLUME			
fluid ounces	28.4	millilitres (ml)	0.0352
quarts (U.K., Canadian)	1.14	litres (L)	0.880
gallons (U.K., Canadian)	4.55	litres (L)	0.220
cubic inches	16.4	cubic centimetres (cm^3)	0.0610
cubic feet	28.3	litres (L)	0.0353
cubic feet	0.0283	cubic metres (m^3)	35.3
cubic yards	0.765	cubic metres (m^3)	1.31
MASS			
ounces	28.3	grams (g)	0.0353
pounds	0.454	kilograms (kg)	2.205
tons	0.907	tonnes (t)	1.10
PRESSURE			
psi (lb/in^2)	6.89	kilopascals (kPa)	0.145
inches of water	0.25	kilopascals (kPa)	4.01
atmospheres	101.3	kilopascals (kPa)	0.00987
ENERGY			
British thermal units (Btu)	1.06	kilojoules (kJ)	0.948
calorie	4.19	joules (J)	0.239
kilowatt hours	3.60	megajoules (MJ)	0.278
Btu/hr	0.293	watts (W)	3.413
Btu/hr/sq. ft.	3.15	watts per square metre (W/m^2)	0.317
POWER			
horsepower	0.746	kilowatts (kW)	1.34
TEMPERATURE			
degrees Fahrenheit	Subtract 32, then multiply by 5/9	degrees Celsius (°C)	Multiply by 9/5, then add 32